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Acoustic pressure sensing with hollow-core photonic bandgap fibers

Adel Abdallah[1, a], Zhang Chaozhu[1, b] and Zhong Zhi[1, c]

[1]Harbin Engineering University, College of information and communication engineering, Nantong Street 145, Nantong district, Harbin city, Heilongjiang Province, P.R. China, 150001

[a]adelmtc39@gmail.com, [b]zhangchaozhu@hrbeu.edu.cn, [c]zhongzhi@hrbeu.edu.cn

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Abstract. Recently, photonic crystal fibers (PCFs) have attracted many researchers because of their special characteristics, and design flexibility that cannot be realized by conventional fibers. One of the important areas of research is the optical fiber hydrophones. In this paper, the finite element solver COMSOL multiphysics (FES) is used to study and compare the phase sensitivity to acoustic pressure of a hollow-core photonic band gap fiber (HC-PBF), and a conventional single-mode fiber (SMF) for various acoustic pressures in the frequency range from 10 kHz to 50 kHz. Simulation results of the investigated optical fibers show that the normalized responsivity (NR) to acoustic pressure of the investigated HC-PBF, and SMF are -344 dB, and -366 dB, respectively.

Introduction

Optical fiber hydrophone is important area of research. For many years, researchers have shown the feasibility of using the conventional SMF hydrophones as an alternative to the conventional sound navigation and ranging (SONAR) technology [1]. However, the conventional SMF is made of glass material that has high Young's modulus, and its pressure-induced change of the effective refractive index of the fundamental mode (n_{eff}) has opposite sign with respect to length change, and hence both compromise NR [2]. As a result, researchers in this area began to search for alternatives to increase NR. One possible solution is to test the microstructured fibers that can be classified into two categories; solid-core PCF (SC-PCF), and HC-PBF. It was shown experimentally that SC-PCF has about the same performance as that of SMF as hydrophone [3]. It was reported that HC-PBFs have many advantages over SMF that contribute to better responsivity to measurands and eligibility for many applications [2, 4, 5]. However, using HC-PBFs as acoustic sensors needs further investigation to be feasible as an alternative to its counterpart of SMF. In this paper, the FES COMSOL multiphysics is used to study NR of the HC-PBF and a SMF by coupling between the acoustic-solid interaction (ASI), and the electromagnetic waves (EMW) modules. The proposed simulation results are based on (HC-1550) and can be applied to other types of HC-PBFs.

Mathematical Model

The PCF is modeled as four circular regions, an air core, an air-silica microstructured inner cladding, a solid silica outer cladding, and an acrylate layer as shown in Fig. 1. The acoustic pressure (P) is governed by the wave equation and is given by [6];

$$\frac{1}{\rho_o c^2}\frac{\partial^2 p}{\partial t^2} + \nabla.\left(-\frac{1}{\rho_o}(\nabla p - q)\right) = Q. \quad (1)$$

where t is the time, ρ_o is the density of the fluid, q and Q are the acoustic dipole and monopole source, respectively. The wave equation can be solved in the frequency domain to expand the acoustic signal into harmonic components by its Fourier series. A harmonic solution has the form;

$$p(x,t) = p(x)e^{i\omega t}. \quad (2)$$

where ω is the angular frequency, and the actual physical value of the acoustic pressure is the real part of Eq.(2), consequently, the time-dependent wave equation reduces to the Helmholtz equation given by;

$$\nabla.\left(-\frac{1}{\rho_o}(\nabla p - q)\right) - \frac{\omega^2}{\rho_o c^2} p = Q. \quad (3)$$

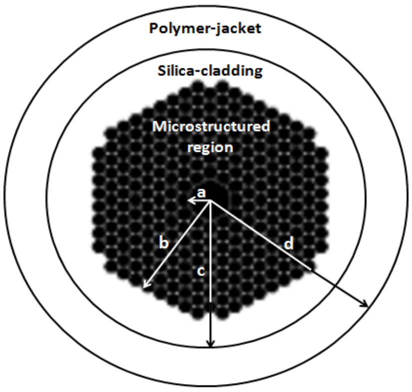

Fig. 1. Cross-section of the investigated HC-PBF with air-core, a microstructured air-silica inner cladding, a solid silica outer cladding and a polymer coating, (a-d) represent the radius of each region.

In the homogenous case where the two source terms q and Q are zero, the solution to the Helmholtz equation is the plane wave given by;

$$\boldsymbol{P} = \boldsymbol{P_o e^{i(\omega t - k.x)}}. \quad (4)$$

Where P_o is the amplitude of the wave and k is the wave number. Considering the investigated fiber as the sensing arm of the interferometric hydrophone, the acoustic pressure (P) primarily affect the fiber length (L), and n_{eff} of the phase (φ) of the travelling light through the fiber, where the phase is given by;

$$\varphi = \frac{2\pi}{\lambda} n_{eff} L. \quad (5)$$

where λ is the wavelength of the propagating light. To calculate n_{eff}, the FES COMSOL multiphysics is used to solve the vectorial electric field wave equation as an eigenvalue problem, then to calculate the propagation constant (β), and n_{eff}. The normalized responsivity of the HC-PBF is given by:

$$NR = \frac{d\varphi}{\varphi(dP)} = \frac{1}{L}\frac{dL}{dP} + \frac{1}{n_{eff}}\frac{dn_{eff}}{dP} = \frac{\varepsilon_z^2}{dP} + \frac{1}{n_{eff}}\frac{dn_{eff}}{dP}. \quad (6)$$

where $\varepsilon_z^2 = dL / L$ is the axial strain of the microstructured region of the HC-PBF.

Simulation results and analysis

The microstructured regions of the PCFs are modeled as anisotropic materials while the silica outer cladding and the acrylate regions are modeled as isotropic materials [2]. The investigated HC- PBF is based on two-dimensional triangular structure with pitch (Λ) 3.8μm (Λ is the central distance between adjacent air-holes in the microstructured cladding), and an air-filling ratio (η) of 96% (η is the ratio of the air-hole diameter in the microstructured cladding to pitch). The index of refraction of silica cladding is 1.4378, and the number of the air-hole rings is eight. Perfectly matched layer

(PML) is used to suppress spurious reflections. The first step of calculations is to perform mode analysis for undeformed fiber. The calculated n_{eff} for undeformed fiber (P = 0) is 0.994893. The second step is to use the acoustics module to apply acoustic pressure of different amplitudes and frequencies that cause structural deformation and the induced stresses and strains in the investigated fibers are calculated. The electromagnetic module exchange data with the acoustics module by coupling between them, then by performing mode analysis, the effective refractive index of the fundamental mode corresponding to the deformed structure is calculated. This allows calculating the phase change and NR given by Eqs. (5), and (6), respectively. Fig. 2 shows the calculated average *NR* for applied acoustic pressure of 1 Pa where the acoustic frequency is swept from 10 kHz to 50 kHz. The calculated NRs for the HC-1550 and SMF are -344 dB, and -366 dB, respectively. We attribute the higher NR of the HC-1550 to its air-core, and the less silica in its microstructured area. This reduces the acoustic pressure-induced n_{eff} change, and increases the pressure-induced length change, consequently, increases its NR.

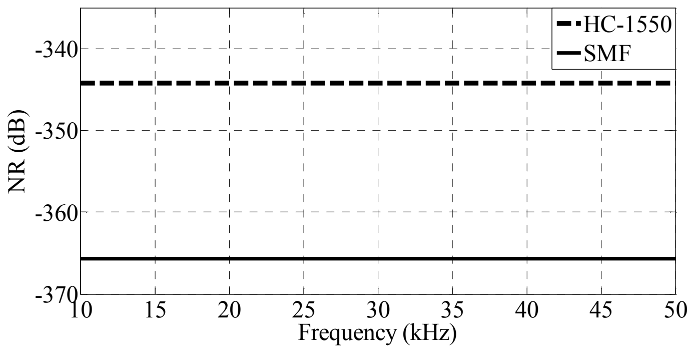

Fig. 2. NR of the HC-1550, and SMF as a function of acoustic frequency for acoustic pressure of 1 Pa.

The experimental results proposed in [2] showed that the *NR* of HC-1550 is about 15 dB higher than the NR of the conventional SMF, while the proposed simulation results indicates a difference of about 22 dB. We attribute this difference to the use of the real structure in [2] that may contain imperfections allows reduction of the *NR* of the HC-1550 compared to the ideal structure that was used in the simulation, in addition, in the calculations we used air-filling ratio of 96% which is higher 6% than that used in [2] which is expected to contribute to higher NR. The effect of changing the structure of the microstructured region on the axial strain, and consequently on NR of the HC-1550 is investigated. The axial strain of the microstructured region of HC-1550 versus η for different applied acoustic pressure is shown in Fig. 3, where Λ is swept from 3.8 µm to 6.3 µm and is allowed to expand to the solid-silica cladding area, while the air-hole diameter (d_h) is unchanged. From Fig. 3, it can be seen that generally, the induced axial strain is proportional to η. This can be attributed to that as η increases, the amount of silica in the microstructured region decreases, consequently, the material is more compressive and the axial strain increases. The effect of the acoustic pressure on n_{eff} of the HC-PBF is calculated and shown in Fig. 4. It can be seen that the calculated n_{eff} for the undeformed HC-PBF is 0.994893, and it increases as the acoustic pressure increases where dn_{eff}/dP is $4.968*10^{-12}$ Pa^{-1} where the acoustic pressure is swept from 0 to 1 GPa at frequecy 10 kHz. As a conclusion, the calculations showed that the acoustic pressure-induced HC-PBF length change is $-3.0545*10^{-11}$ Pa^{-1}, the acoustic pressure-induced n_{eff} change is $4.968*10^{-12}$ Pa^{-1}, and the phase sensitivity to acoustic-pressure of the investigated HC-PBF is $-2.5577*10^{-11}$ Pa^{-1}. The contribution of the index change term to NR of the HC-PBFs is minor with respect to the fiber length change. However, for accurate design and simulations of the HC-PBFs, the index change term should be taken into account.

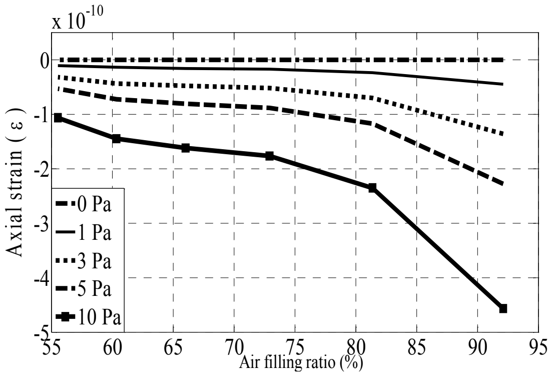

Fig. 3. Axial strain of the microstructured region of HC-1550 as a function of η for different acoustic pressures.

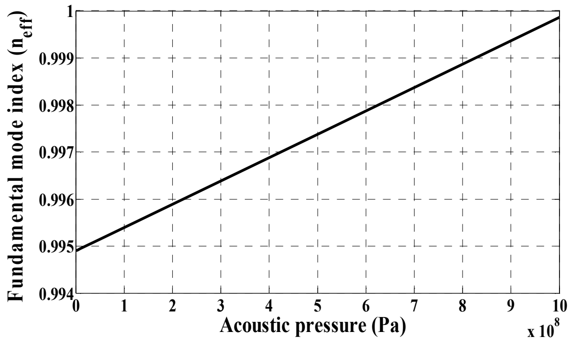

Fig. 4. The fundamental mode refractive index of the investigated HC-PBF as a function of the acoustic pressure at acoustic frequency 10 kHz.

Conclusion

In this paper, the FES COMSOL multiphysics is used to calculate the phase sensitivity to acoustic pressure of a HC-PBF and conventional SMF. The proposed simulation results showed that NR of the HC-PBF is 22 dB higher than SMF for the same applied acoustic pressure and frequency. This higher NR is as a result of its air core, less silica, and the high air-filling ratio in the microstructured area allows the induced axial strain to increase and consequently, the NR. It was shown that the acoustic pressure-induced HC-PBF length change is $-3.0545*10^{-11}$ Pa^{-1}, the acoustic pressure-induced n_{eff} change is $4.968*10^{-12}$ Pa^{-1}, and consequently, the phase sensitivity to acoustic-pressure of the HC-PBF is $-2.5577*10^{-11}$ Pa^{-1}.

Acknowledgements

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